SESSION IX: Functional Components

FM 9.5: Germanium Photodiode Circuits Suitable for Measuring Extremely High Temperatures and Extremely Small Temperature Changes

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THE FREQUENCY RESPONSE of germanium and silicon types of *pn* photodiodes, when measured by modulated radiation, has been found to be identical, with the response falling off between *10* and *20 kc,* and gradually dropping to zero. The physical causes of this response characteristic are only partly understood. In most photodiodes, using reverse bias, at currents of *20-60* μa, flicker noise persists up to frequencies above *10 kc*. Thus, within the flat part of the frequency response curve, no region free of flicker noise may be found. However, some selected germanium photodiode types disclosed a drop in flicker noise below shot noise at about *1-2 kc*. In these photodiodes, a shot-noise region, showing white noise, has been found to exist within the flat part of the frequency response curve, as shown in Figure 1.

A noise theory of photodiodes, including photon noise, has been evolved using *Boltzmann* statistics for the absorption process. This theory is essentially similar to one offered by *A. van der Ziel*[5]. The mean square noise current is presented in equation *1*. The coefficient α indicates the mean number of electrons per photon impinging on the photodiode. The quantities x and μ are related to the radiation source, supposedly a black body. Equation *1* has been well confirmed experimentally[1, 3] within the shot-noise region of the photodiodes.

At values of x, which are small with respect to unity, the quantity μ is approximately equal to $kT/h\nu$. Hence, in this case, the quantity γ according to equation *2* becomes approximately equal to $\alpha\ kT/h_\nu$. Thus, the photodiode noise according to equation *1* becomes approximately proportional to the radiation temperature T. The region, where this approximation[1, 2, 4] holds good, may be seen from Figure 3.

A high-temperature radiation source, consisting of an arc discharge (in argon) at an atmospheric pressure at *200 a* arc current, was developed for our studies. The highest temperature in the discharge was estimated by spectrometry to be about *20,000° K*. At a mean frequency of radiation of about 2×10^{14} *cps* it was found that γ is about 1.3; Figure 3. A measured curve† of γ with a photodiode of the type shown in Figure 1, dependent on frequency, is shown in Figure. 4. There seems to be little doubt that this curve confirms the foregoing theory. The upward trend of the curve below *8 kc* is due, in part, to flicker noise and also to noise caused by arc instability. The drop of the curve above *20 kc* is due to reasons similar to those responsible for the drop of the curves above such frequencies shown in Figure 1.

Improvements in techniques might decrease the rise of the curve in Figure 4 below *8 kc*. By the use of two photodiodes on which the radiation from the arc impinges, the noise caused by its instability, being coherent, may be blotted out. This result was obtained in preliminary measurements††. Hotter arcs now being prepared will lead to higher values of μ and γ. The theory resulting in equation *1* is based on the statistics of *Boltzmann*. If the statistics of *S. N. Bose* are applied, the factor γ in equation *1* must be replaced by μ. Information in Figure 4 serves as experimental evidence that the former statistics are valid.

The mean power at a mean frequency ν, emitted by an aperture of relatively small area A in the enclosure of a black-body radiation space of temperature T appears in equation *5*. Here $\Delta\nu$ is the bandwidth at a mean frequency υ. Computing equations 6 and 7 and solving for ΔT equation *8* is obtained. The universal function Q of υ and T is shown in Figure 6. Its minimum value Q_{min} occurs at $x = 3.83$ and is equal to $3.66 \times 10^{-3°}$ *K-meter*. The formula for Q is in equation *9*. The noise-figure F of the photodiode can be defined as the ratio of available noise power to available signal power at the output, divided by the equivalent ratio at the input. Using a photodiode, the minimum measurable value[4] of ΔT is given by equation *10*. Obviously, this value decreases, if Δf over $\Delta\upsilon$ is decreased, Δf being the noise bandwidth and $\Delta\upsilon$ the radiation bandwidth. This may be 10^{-13}. Thus, if $A = 1\ mm^2$ and $F = 2$, $\Delta T_{min} = 2.3 \times 10^{-6°}$ K is obtained. The noise figure of photodiodes has been calculated and measured[6]. It is about *2* for the diodes shown in Figure 1. The available gain of these photodiodes is about *15*. Hence, we have device circuits, which allow measurements of extremely small temperature changes, as well as extremely high temperatures.

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† Curve prepared by *Werner Gubler*.

†† Measurements made by *Werner Gubler*.

[1] Spescha, G., "Experimentelle Untersuchungen ber über spontane Photonenschwankungen," *Thesis*, Swiss Federal Institute of Technology; 1959.

[2] Spescha, G., and Strutt, M. J. O., "Theoretische Ueberlegungen zur Experimentellen Bestimmung der Spontanen Photonenschwankungen," *Helvetica Physica Acta,* vol. 133, p. 53-68; 1960.

[3] Spescha, G., and Strutt, M. J. O., "Experimentelle Bestimmung der Spontanen Photonenschwankungen; *Helvetica Physica Acta,* vol. 133, p. 69-88; 1960.

[4] Strutt, M. J. O., "Ueber die kleinstein Messbaren Temperaturändergen," *Archiv der Elektrischen Uebertragung,* vol. 15, p. 355-358; 1961.

[5] van der Ziel, A., "Noise," *Prentice-Hall,* p. 112; 1954.

[6] Strutt, M. J. O., "Berechnungen der Rauschzahl und der Leistungsverstärkung von Photodioden, *Archiv der Elektrischen Uebertragung;* to be published.

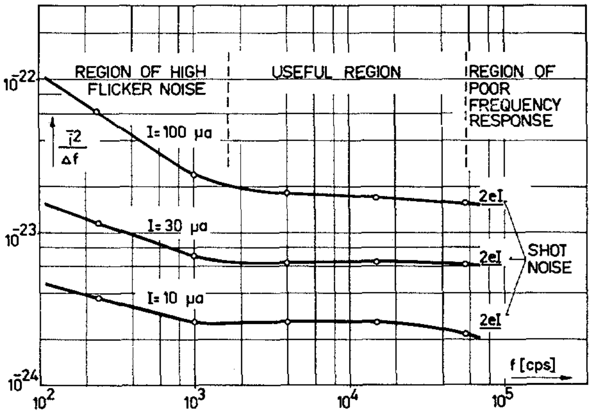

Figure 1—Mean square noise current for a selected germanium photodiode. The useful region is bounded by flicker noise and falling frequency response.

(1) $\overline{i^2} = 2e(I-I_0)\gamma\Delta f + 2eI_0\Delta f$

(2) $\gamma = 1 + \alpha(\mu - 1)$

(3) $\mu = \frac{\exp(x)}{\exp(x)-1}$

(4) $x = \frac{h\nu}{kT}$

I = MEAN DC CURRENT

I_0 = DARK CURRENT

Δf = NOISE BAND WIDTH

e = ELECTRON CHARGE

h = PLANCK'S CONSTANT

T = TEMPERATURE

k = BOLTZMANN'S CONSTANT

α = QUANTUM EFF.

ν = RADIATION FREQUENCY

Figure 2—Equations establishing the relations for diode-noise current in terms of diode and radiation properties.

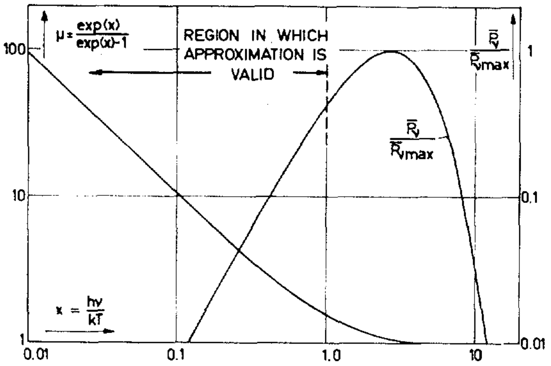

Figure 3—Plot for $P/P\nu_{max}$, the power radiated from a black body aperture over its maximum value, dependent on $x = h\nu/kT$, where μ is dependent upon x.

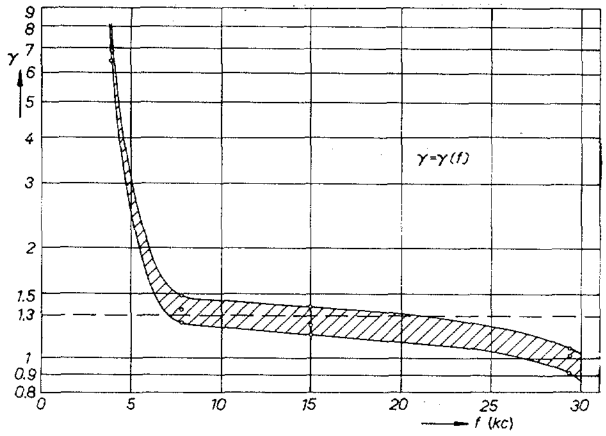

Figure 4—Experimental curve of ν (*vertical*), dependent on frequency at a radiation temperature of about *20,000° K.*

(5) $\bar{P}_\nu = \frac{2A\pi h\nu^3\Delta\nu}{c^2(\exp x - 1)}$

(6) $\frac{\Delta\bar{P}_\nu}{\Delta T} \approx \frac{d\bar{P}_\nu}{dT} = \bar{P}_\nu \mu \frac{x}{T}$

(7) $\Delta\bar{P}_\nu = \sqrt{\overline{(\Delta P_\nu)^2}}$

(8) $\Delta T = Q(\nu,T)\sqrt{\frac{\Delta f}{A\Delta\nu}}$

(9) $Q = \frac{2hc}{k\sqrt{\pi}}\frac{\sinh\left(\frac{x}{2}\right)}{x^2}$

(10) $\Delta T_{MIN} = Q_{MIN}F\sqrt{\frac{\Delta f}{A\Delta\nu}}$

c = VELOCITY OF LIGHT

A = AREA

F = NOISE FIGURE

Figure 5—Equations that lead to the minimum observable value of temperature change.

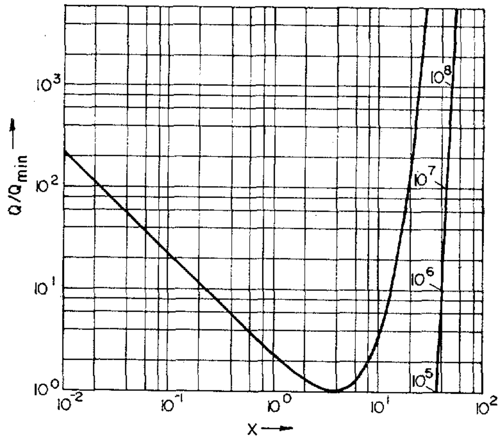

Figure 6—Ratio Q/Q_{min} as dependent on x. The value Q_{min} occurs at $x = 3.83$ and is equal to $3.66 \times 10^{3°}$ *K-meter.*